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Combined Effects of Geomechanical Deformation and Geometric Distribution on Flow and Transport Behaviors in Fractured Media

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Research Background

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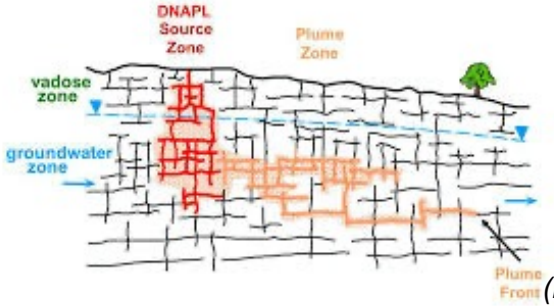
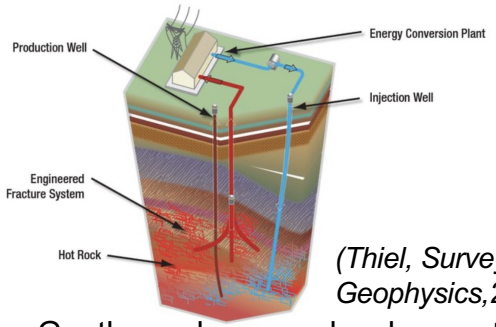
Transport in fractured media is relevant to a wide range of geoscience and geoengineering applications



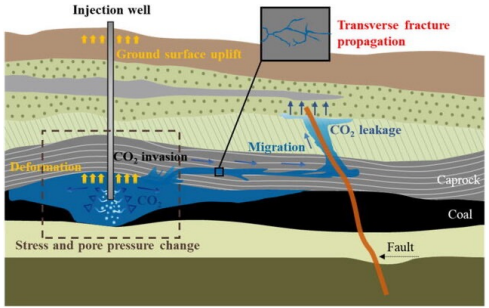
(Parker, 2013)

Groundwater contamination remediation



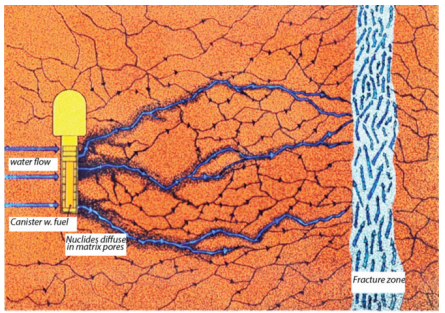
(Thiel, Surveys in Geophysics,2017)

Geothermal energy development



(Ge et al., Physics of Fluids, 2024)

CO_2 geological storage



(Tsang et al., WRR, 2015)

Nuclear waste disposal

Complexity of Transport Behavior in Fractured Media

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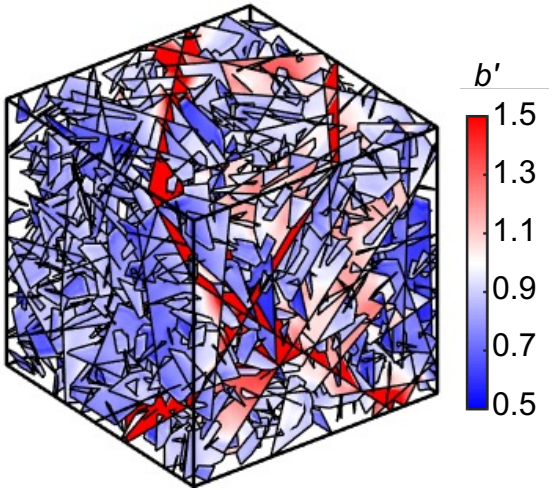
Fractured media exhibit multi-scale heterogeneity:

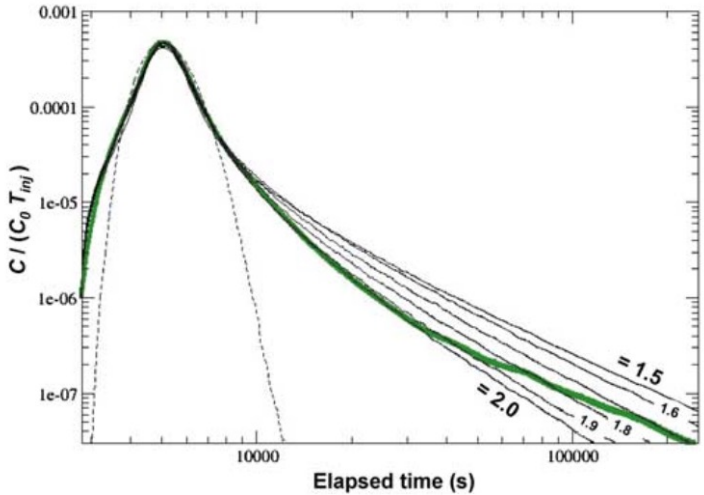
- Aperture heterogeneity at the fracture scale
- Topological and geometric complexity at the network scale

Non-Fickian transport (or anomalous transport), characterized by:

- Early arrival
- Long tailing
- Non-Gaussian solute plume



(Jiang and Lei, 2025, Computer and Geotechnics)



(Gouze et al., 2008, WRR)

Role of Geomechanics in Transport in Fractured Media

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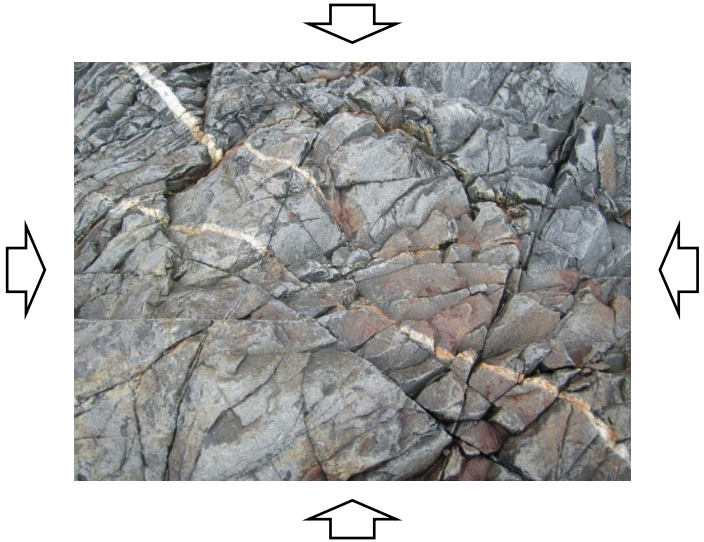
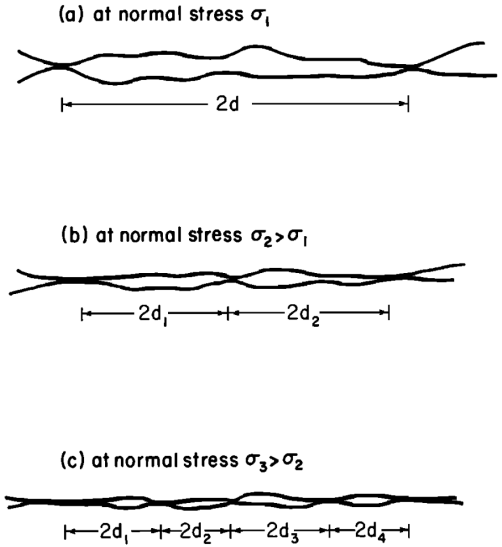
Geomechanics governs fracture aperture heterogeneity through the following mechanisms:

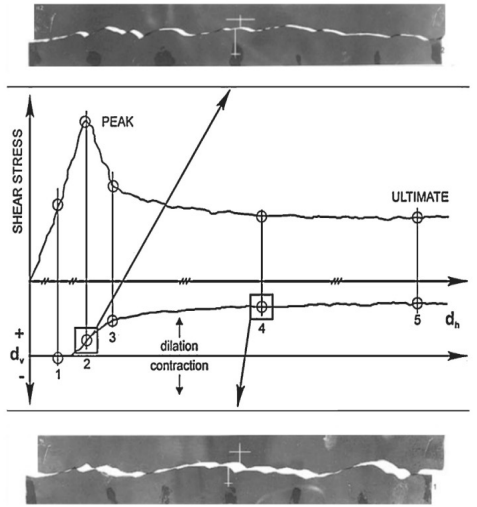
- Nonlinear *normal closure,*
- Shear slip-induced dilatancy (*shear dilation*),

thereby affecting the flow and transport behaviors of fractured media





Tsang and Witherspoon, 1981, JGR



Barton, 1973; Barton and Choubey, 1977

Key Scientific Questions and Challenges

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Natural or human activities can ***perturb local stress fields***, triggering abrupt changes in the heterogeneity of fracture systems. Therefore, it is important to understand how transport behaviors change accordingly, which is helpful for **upscaling**.

Challenge of 3D DFN studies:

Geomechanical modeling requires the computation of the rock matrix deformation

→ High computational cost and meshing problems caused by the stochastic DFN geometry

Existing 3D DFN generators (e.g., dfnWorks) cannot well address the meshing problems linked with the rock matrix

Solution:

An in-house 3D DFN generator (**FracLab**) was developed, with geometric optimization functions included

FracLab (in-house code): DFN generation with high-quality meshing

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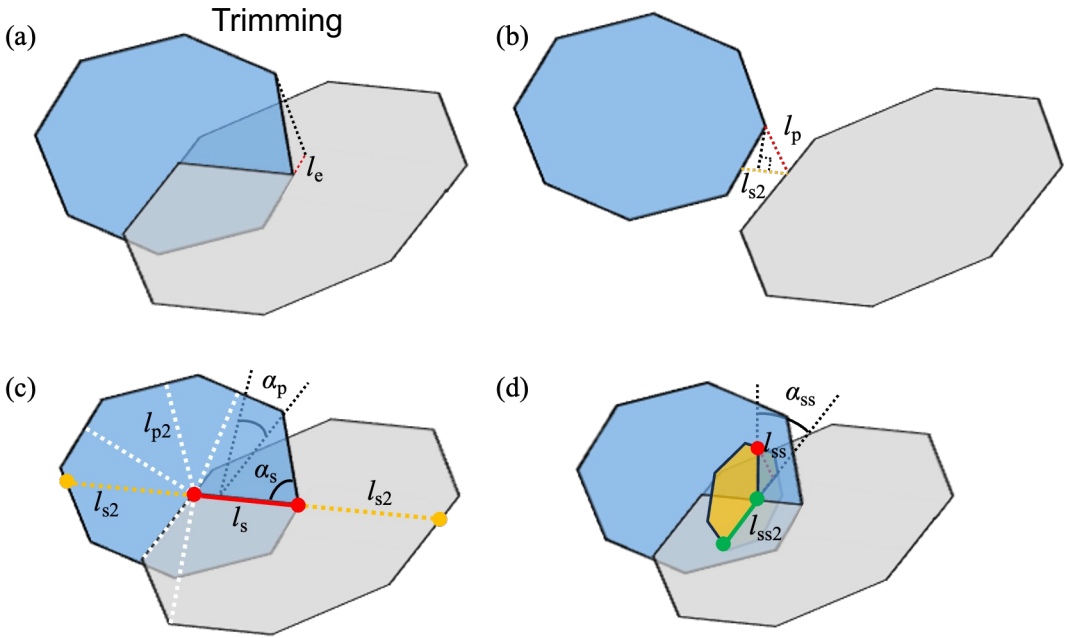
Rejection algorithm for ensuring high mesh quality for **both fracture and matrix domains**

- Intersection length
- Distance between intersections
- Distance between intersection ends and polygon vertices
- 6 boundaries are regarded as 6 fractures
- Distance between intersection ends and intersection segments
- Distance between intersection ends and polygon boundaries
- Distance between polygon vertices and intersection segments
- Angle between two intersecting fractures
- Angle between the intersection segments of fractures
- Distance of polygon vertices to other polygons (to be considered in version 3)



Jiang and Lei, 2025, Computer and Geotechnics

FracLab (in-house code): DFN generation with high-quality meshing

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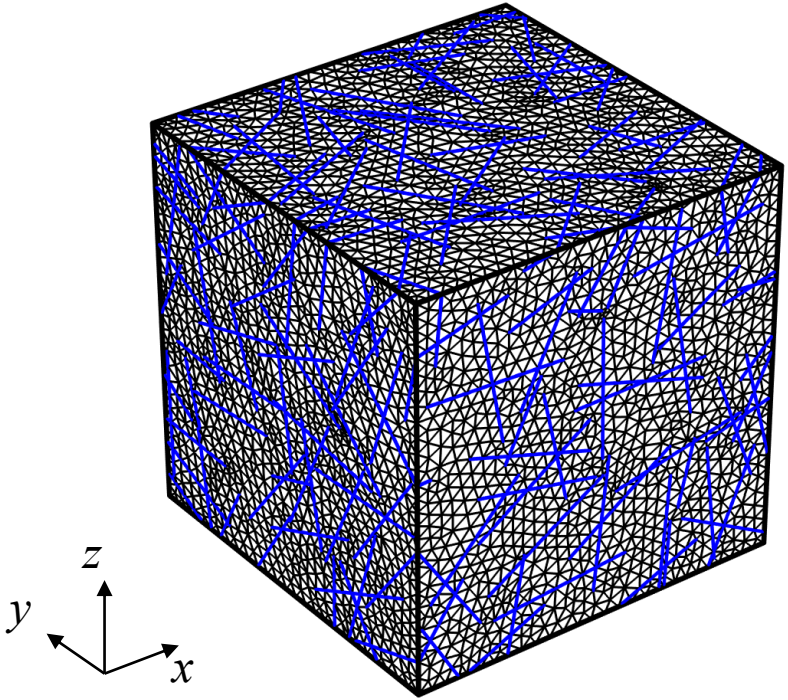
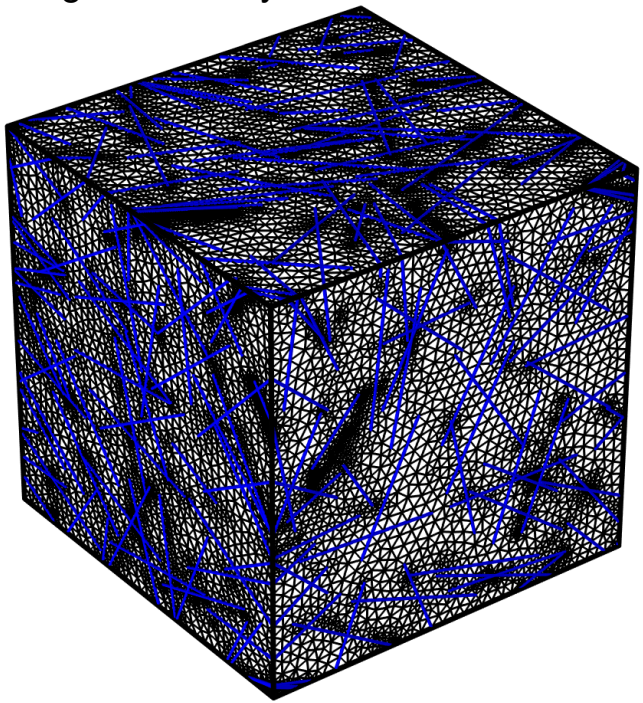
High-quality meshing with a smaller number **enables** coupled stress-flow-transport modeling in 3D

DFN generated by **FracLab** and the meshing



DFN generated by **dfnWorks** and the meshing



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Workflow for coupled stress-flow-transport modeling in 3D fractured media

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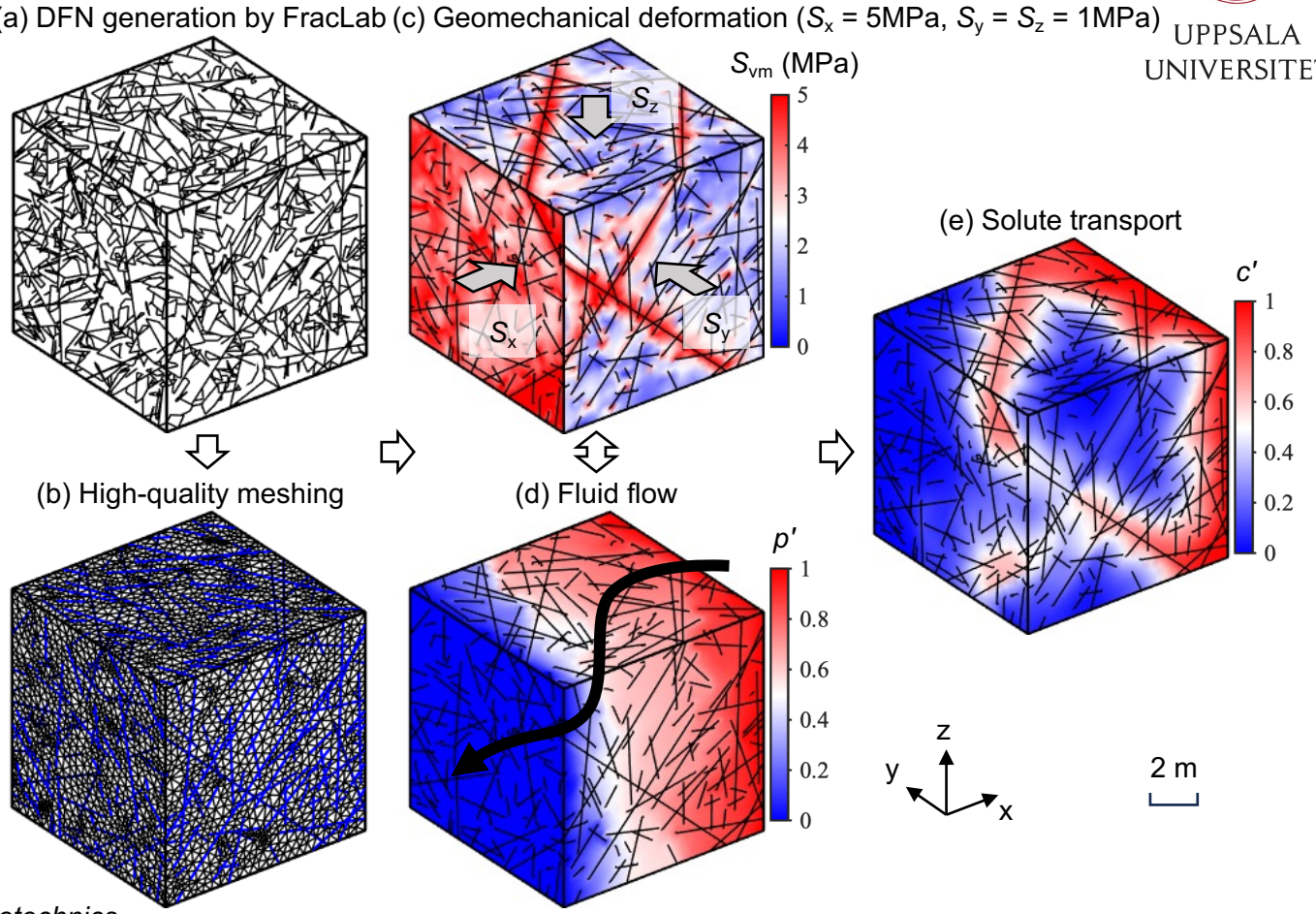
One DFN example:

2000 fractures

Power-law model for radii (a = 3)

$$f(l) = \alpha r^{-a}, \quad r \in [r_{\min}, r_{\max}]$$

Orientation and positions of fractures are random



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Mathematical models

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Mechanical deformation

The quasi-static momentum balance equation for the rock matrix:

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{F} = 0$$

Fracture-matrix interactions:

$$\boldsymbol{\sigma} \cdot \mathbf{n}_{\mathrm{f}}^{+} = -\alpha_{\mathrm{f}} p \mathbf{I} \cdot \mathbf{n}_{\mathrm{f}}^{+} - \mathbf{t}_{\mathrm{f}}^{+}$$
$$\boldsymbol{\sigma} \cdot \mathbf{n}_{\mathrm{f}}^{-} = -\alpha_{\mathrm{f}} p \mathbf{I} \cdot \mathbf{n}_{\mathrm{f}}^{-} - \mathbf{t}_{\mathrm{f}}^{-}$$

Fracture mechanical behaviors:

Non-linear normal closure:

$$\sigma_{\mathrm{n}}' = -\frac{K_{\mathrm{ni}} u_{\mathrm{n}}}{1 + u_{\mathrm{n}}/u_{\mathrm{m}}}$$

Non-linear shear slip:

$$\boldsymbol{\tau} = \min\left(\frac{\tau_{\mathrm{c}}}{\| \boldsymbol{\tau}_{\mathrm{trial}} \|}, 1\right) \boldsymbol{\tau}_{\mathrm{trial}} \qquad \tau_{\mathrm{c}} = \mu \sigma_{\mathrm{n}}'$$
$$\boldsymbol{\tau}_{\mathrm{trial}} = \boldsymbol{\tau}_{\mathrm{old}} - K_{\mathrm{s}} \Delta \mathbf{u}_{\mathrm{s}}$$

Shear dilation:

$$\Delta u_{\mathrm{d}} = \begin{cases} \tan\beta_{\mathrm{d}} \Delta u_{\mathrm{s}}, & 0 \le u_{\mathrm{s}} \le u_{\mathrm{r}} \\ 0, & else \end{cases}$$

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Fluid flow

Fracture: $\nabla \cdot (\rho \mathbf{v}_{\mathrm{m}}) = 0 \qquad \mathbf{v}_{\mathrm{m}} = -\frac{k_{\mathrm{m}}}{\eta} \nabla p$

Rock matrix: $\nabla_{\tau} \cdot \left(b \rho \mathbf{v}_{\mathrm{f}}\right) = \rho \left(q^{+} + q^{-}\right) \qquad \mathbf{v}_{\mathrm{f}} = -\frac{k_{\mathrm{f}}}{\eta} \nabla_{\tau} p$

Solute (conservative) transport

Fracture: $\frac{\partial(\phi c)}{\partial t} + \nabla \cdot (\mathbf{v} c) = \nabla \cdot (\phi \mathbf{D} \nabla c)$

Rock matrix: $b \frac{\partial c}{\partial t} + \nabla_{\tau} \cdot (\mathbf{v} c) = \nabla_{\tau} \cdot \left(b \mathbf{D} \nabla_{\tau} c\right) + \zeta^{+} + \zeta^{-}$

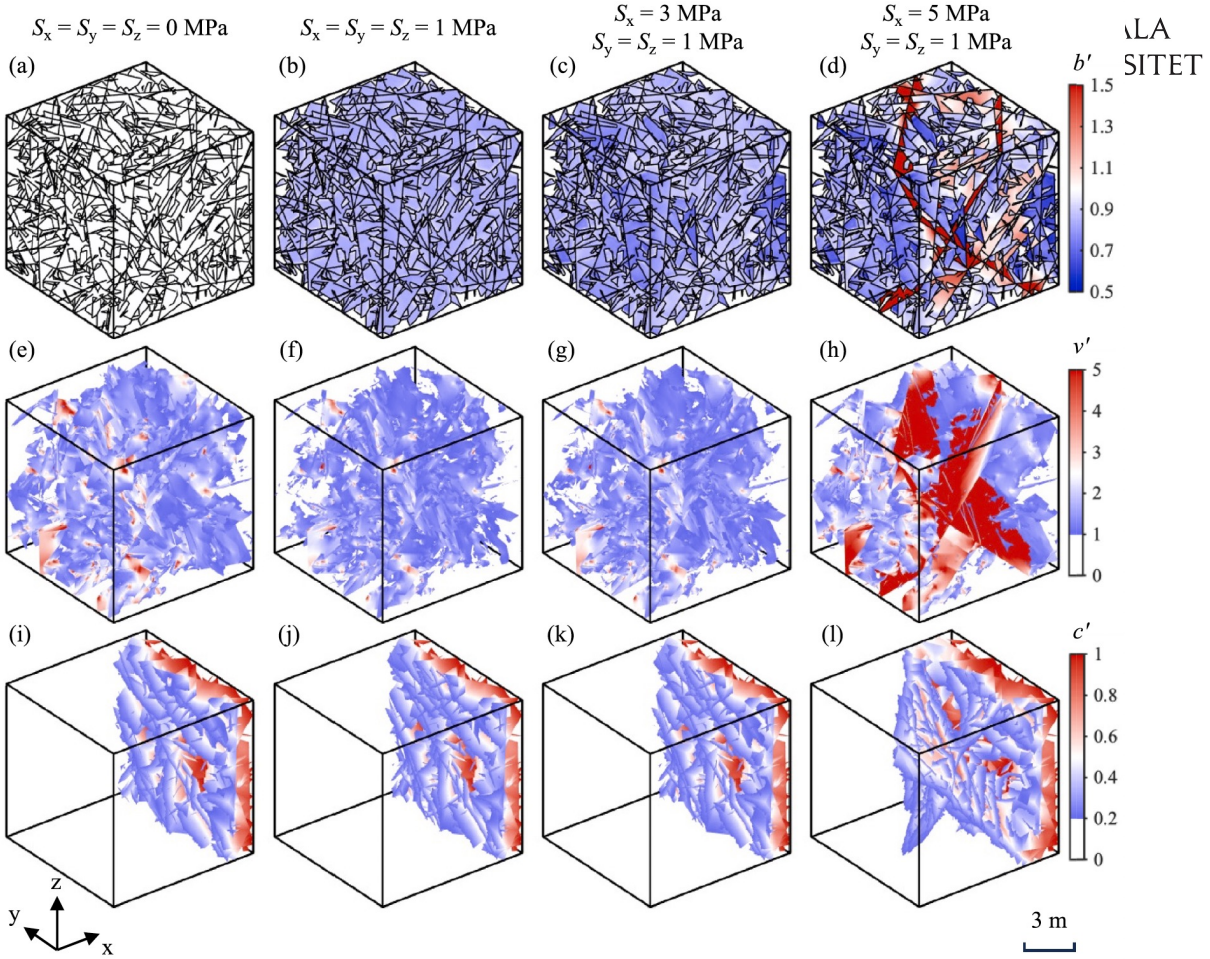
Fracture mechanical aperture:

$$b = \begin{cases} b_0 + u_{\mathrm{n}}, & \sigma_{\mathrm{n}}' < 0 \\ b_0 + u_{\mathrm{n}} + u_{\mathrm{d}}, & \sigma_{\mathrm{n}}' \ge 0 \end{cases}$$

A case study with a constant initial aperture

- **Isotropic stress** -> uniform normal closure and little dilation -> no change of plume shape, and delayed breakthrough

- **Anisotropic stress with a high stress ratio** -> pronounced shearing and dilation -> strong flow channeling -> early breakthrough



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Quantitative analysis

Aperture heterogeneity indicator:

$$\chi = \frac{\left(\iint b \, \mathrm{d}S\right)^2}{S \iint b^2 \, \mathrm{d}S},$$

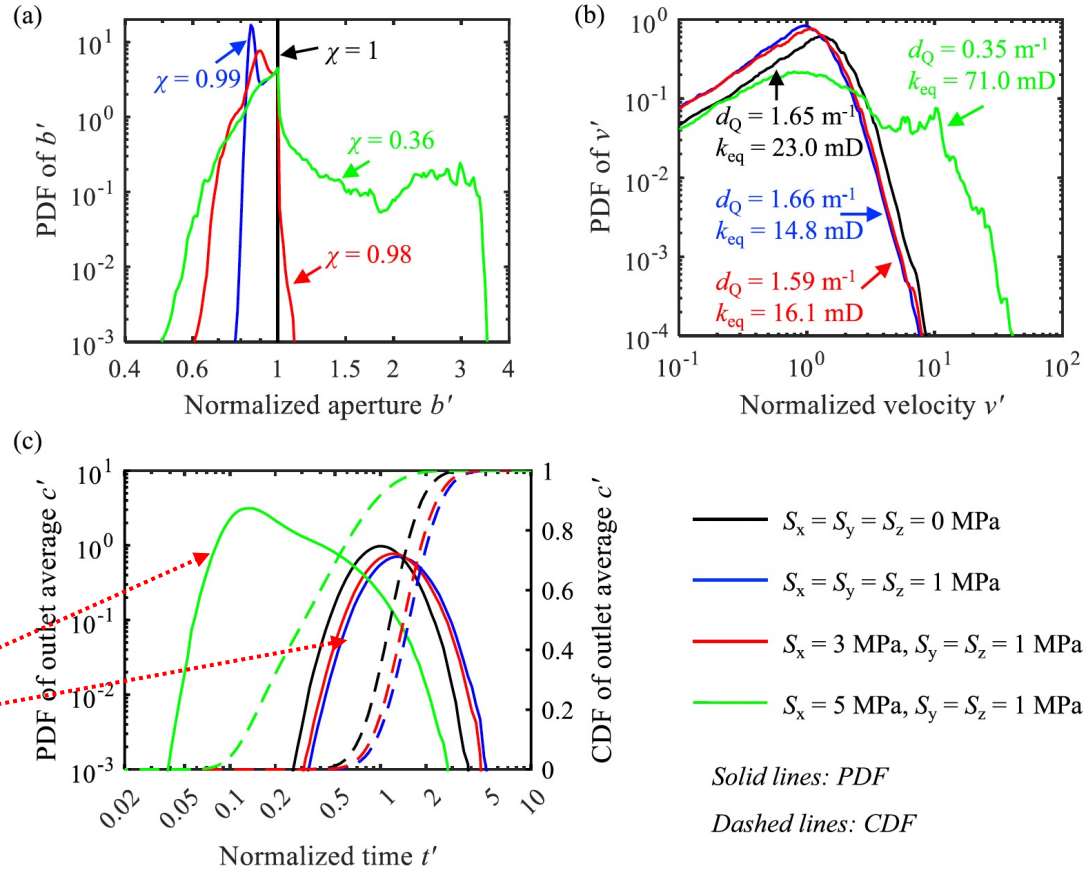
Flow channeling density indicator

$$d_{\mathrm{Q}} = \frac{1}{L^3} \frac{\left(\iint q \, \mathrm{d}S\right)^2}{\iint q^2 \, \mathrm{d}S},$$

Equivalent permeability

$$k_{\mathrm{eq}} = \frac{\mu Q}{L \rho g (h_{\mathrm{in}} - h_{\mathrm{out}})}.$$

Stress-induced transition from Fickian to non-Fickian transport



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A case study with a variable initial aperture

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More realistic settings

Aperture verifiability

Inter-fracture $b_{0,\max} = C_1\sqrt{R}, C_1 = 5e-5$ *(Olson et al., JGR, 2003)*

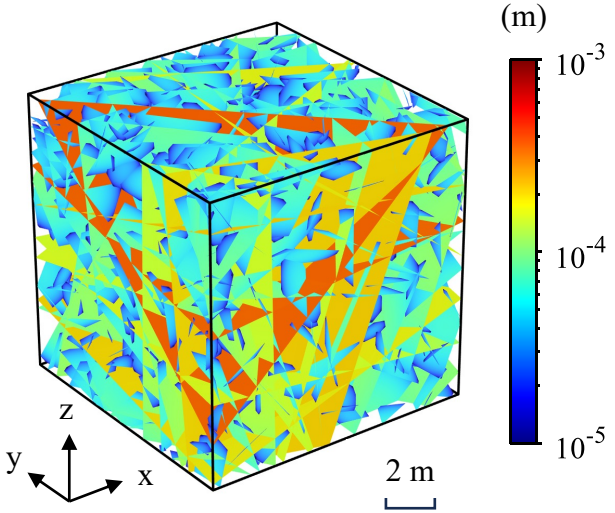
Intra-fracture $b_0(r) = b_{0,\max}\sqrt{1-\frac{r^2}{R^2}}$ Elliptical distribution

Stiffness verifiability

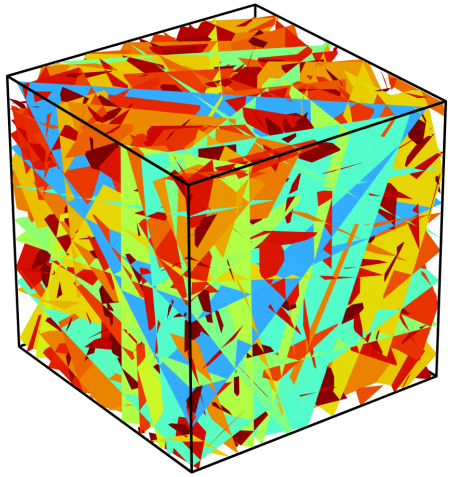
$K_{ni} = \frac{C_2}{2R}, C_2 = 600\ \text{GPa}$ *(Lei, JAG, 2022)*

$K_s = K_{ni}/5$

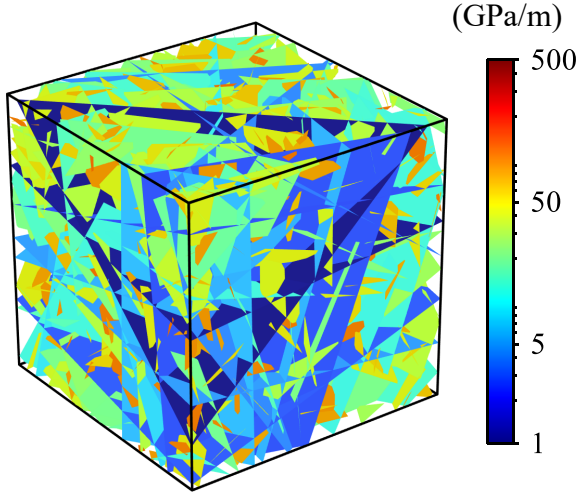
Initial aperture b_0



Initial normal stiffness K_{ni}



Shear stiffness K_s



Geomechanical deformation

Isotropic stress -> non-uniform closure -> **reduce** aperture heterogeneity

Anisotropic stress -> shear dilation -> increase aperture heterogeneity

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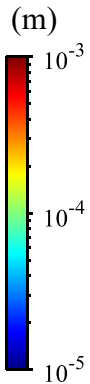
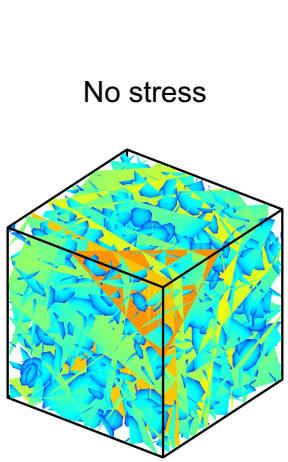
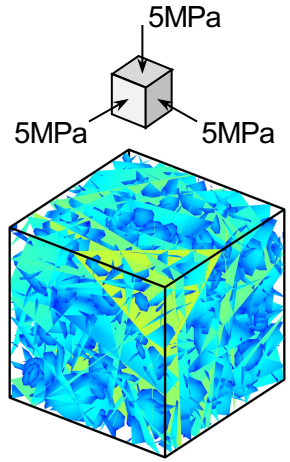
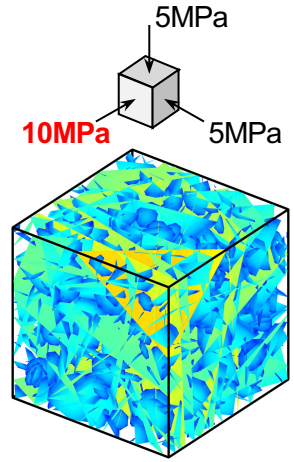
Aperture heterogeneity indicator:

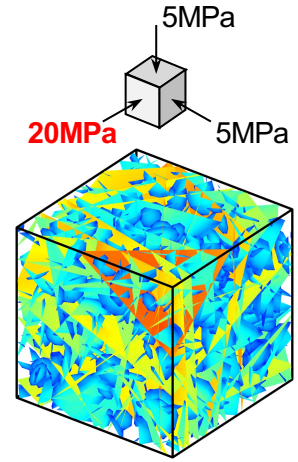
$$\chi_b = \frac{\left(\iint_{A_f} b \, dA_f \right)^2}{A_f \iint_{A_f} b^2 \, dA_f}$$

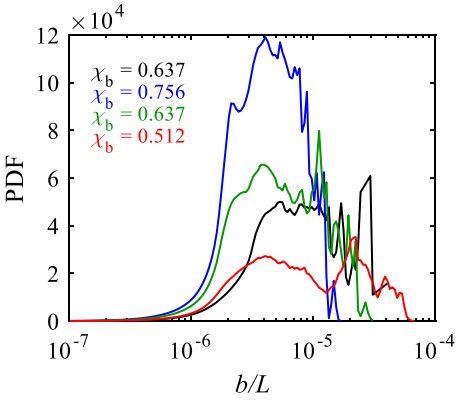


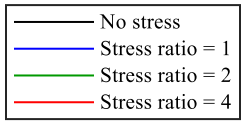


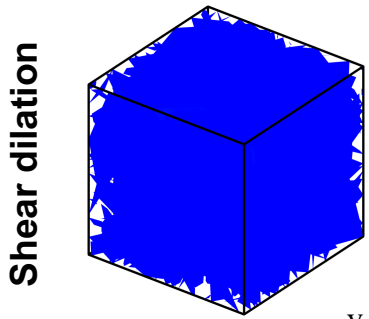


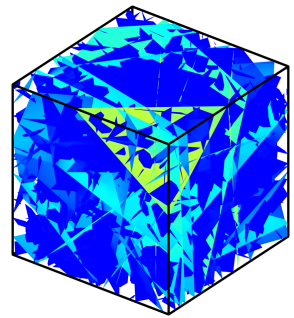


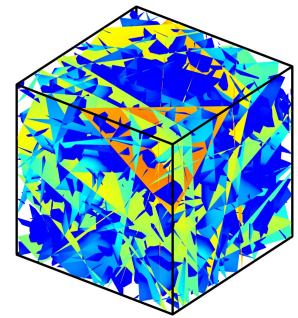


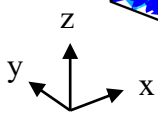












Fluid flow

Isotropic stress -> reduce aperture heterogeneity -> weaken flow channeling

Anisotropic stress -> increase aperture heterogeneity -> **also weaken flow channeling?**

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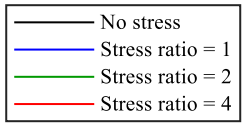
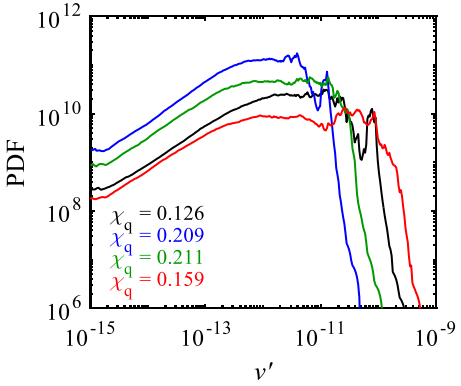
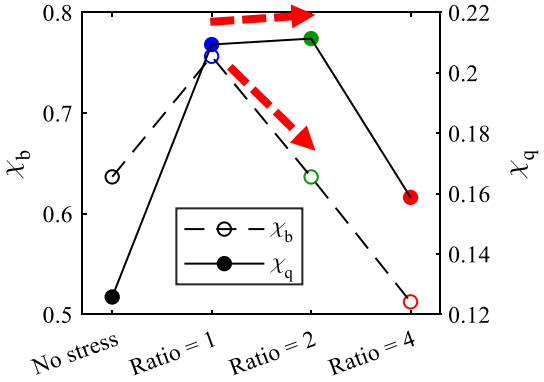


Flow localization indicator:

$$\chi_q = \frac{\left(\iint_{A_f} q \, dA_f\right)^2}{A_f \iint_{A_f} q^2 \, dA_f}$$

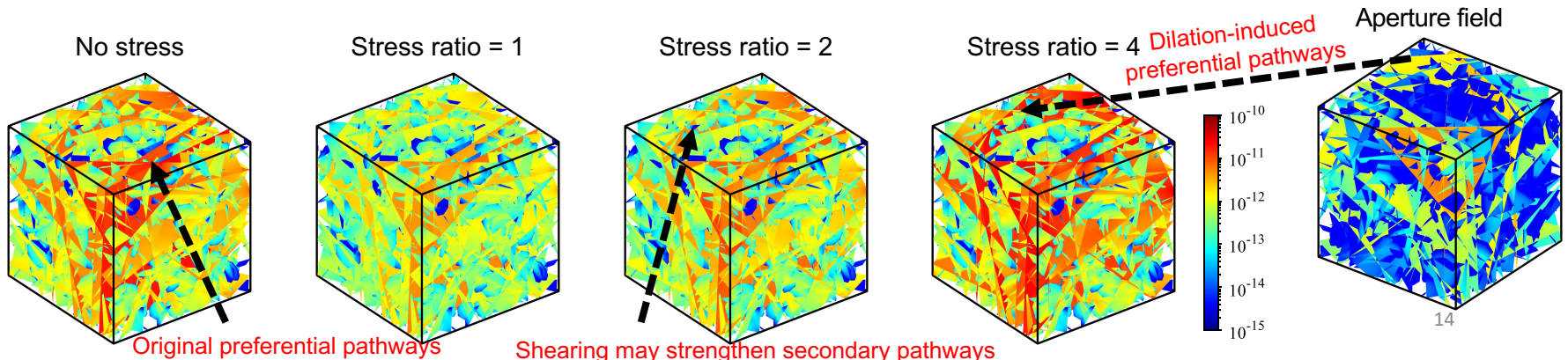




Competition exists:
Unstressed geometry-controlled preferential pathways (linked with topology and size-controlled aperture)

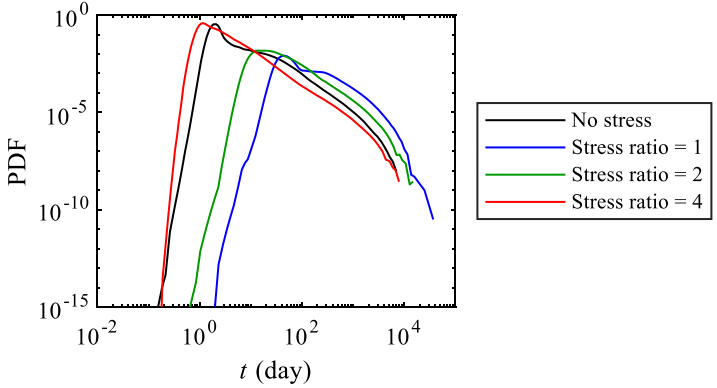
VS

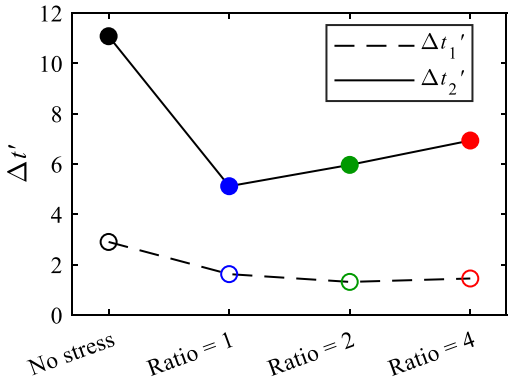
Shear dilation-induced preferential pathways



Solute transport

Shear dilation may **compete** with the preferential flow channels developed under unstressed conditions, promoting a more uniform flow field and even **smoothing out** the early non-Fickian breakthrough behavior.





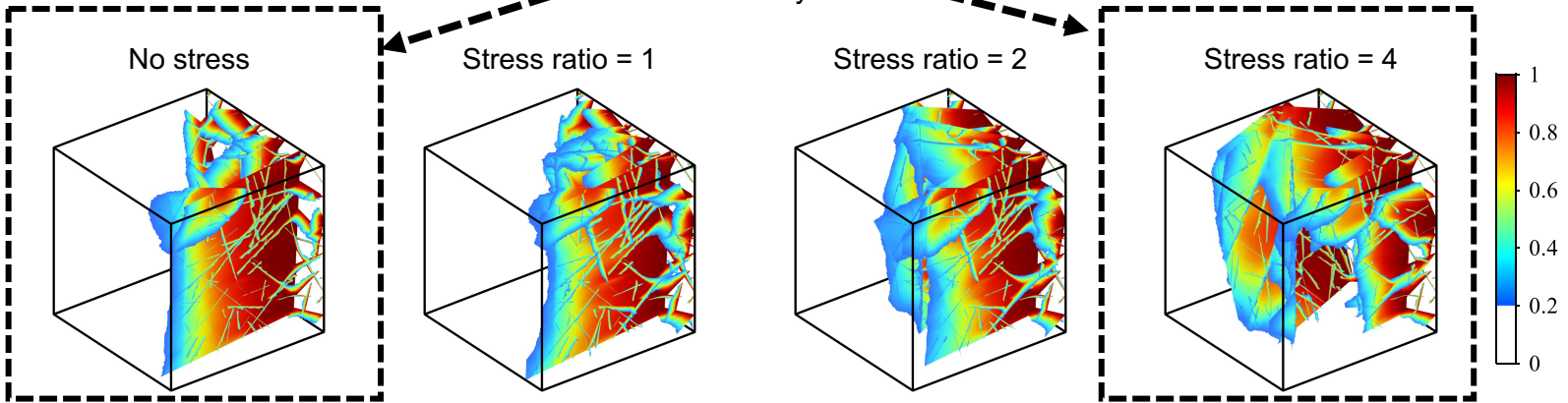
Breakthrough time width:

$$\Delta t_1' = \frac{t_{70} - t_{30}}{t_{50}}$$

$$\Delta t_2' = \frac{t_{90} - t_{10}}{t_{50}}$$

Impacted more by the rock matrix

Two different systems



Uncertainty of stress-dependent flow and solute transport

Geometry-controlled and dilation-induced preferential pathways

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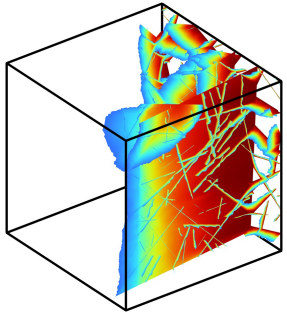
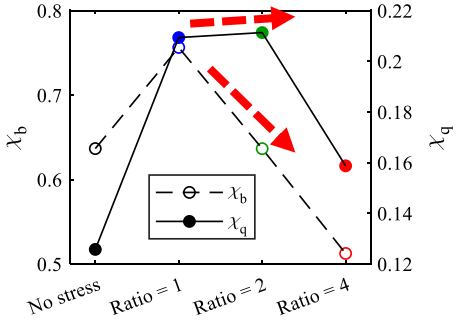
Compete with each other

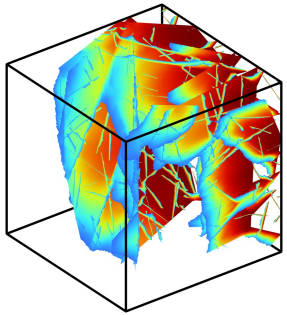
Realization 1

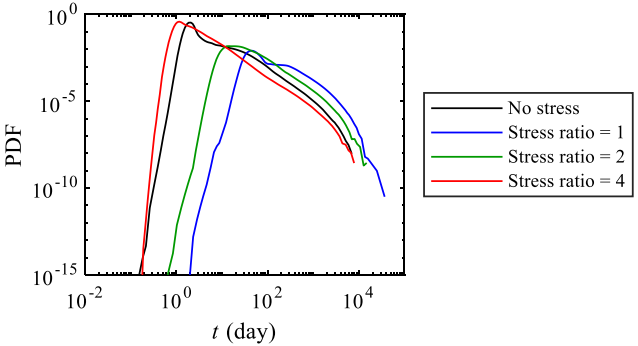
No stress





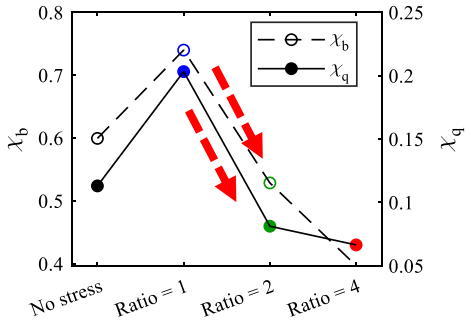
Stress ratio = 4



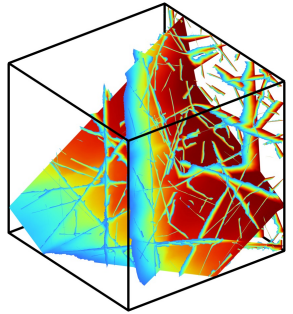


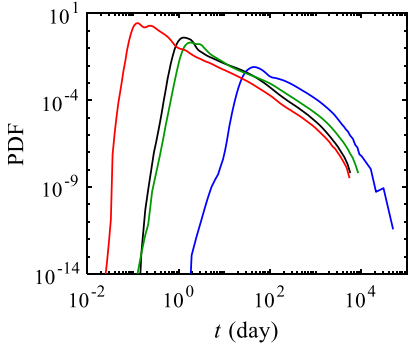
Act synergistically

Realization 2

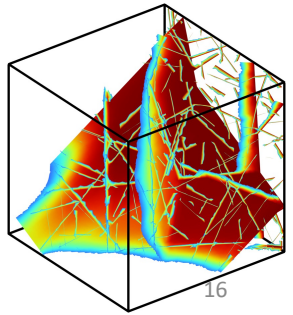


No stress





Stress ratio = 4



Take-home massages

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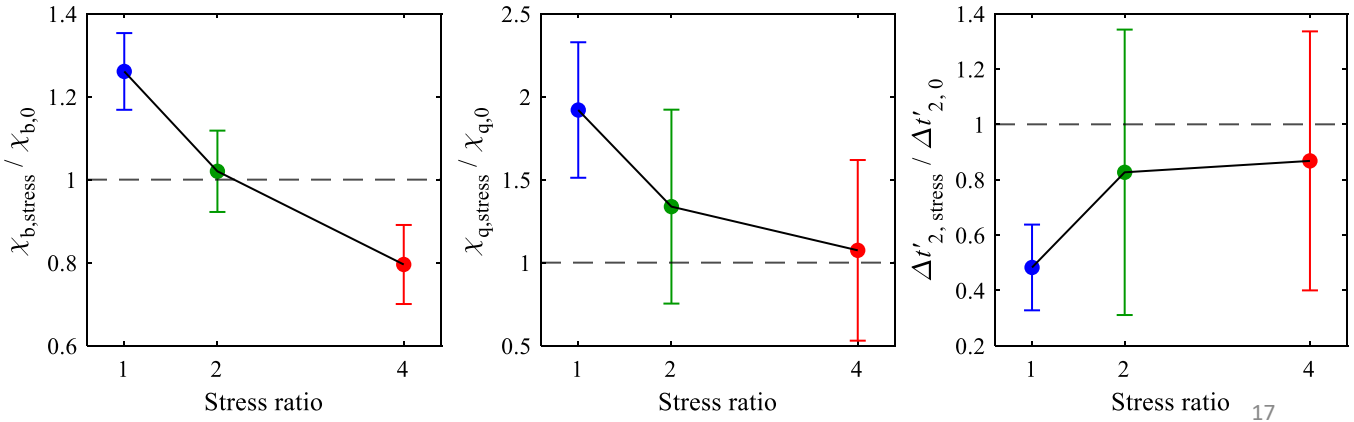
Stress-induced non-uniqueness / stochasticity amplification:

1. Even with identical macroscopic geometric statistical parameters (e.g., P_{32} and a), different realizations behave differently: anisotropic stress loading may enhance aperture heterogeneity, but it does not necessarily intensify flow localization.

2. This thereby increases the uncertainty of anisotropic stress-induced flow and transport behaviors. It also significantly increases the difficulty of upscaling.

The ratio between the properties under stressed and unstressed conditions



Strål säkerhets myndigheten
Swedish Radiation Safety Authority

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We gratefully acknowledge the Swedish Radiation Safety Authority (SSM) for their financial support of this project.

Thanks for your attention!